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Vibration of Bundled and Single Conductors: A Comparative Case Study

A. S. RICHARDSON

Research Consulting Associates, 3 Wingate Rd., Lexington, MA 02173 (U.S.A.)

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ABSTRACT

During the time period from December 7 - 13, 1985, a series of field tests was undertaken in Littleton, New Hampshire, for the New England Power Company. The purpose of the tests was to measure the aeolian vibration in the new DC transmission line conductors. The objectives were (a) to evaluate the performance of the damping devices installed on the phase I line, and (b) to provide design data for specifying vibration control devices for the phase II line.

Both of the objectives have been met. The overall conclusions are:

(i) No damping devices are needed in the ground return, or in the bundle of three conductors, in order to meet or satisfy IEEE standard stress criteria (150 microstrain), regardless of how many spacer/dampers may be used (from one to five per span).

(ii) There is no perceivable change in the vibration level of the bundle compared with that of the single ground return conductor when two, then four, spacer/dampers are removed.

(iii) At all times during the measurement period, including overnight continuous recording of up to twenty hours, the vibration level of the triple bundle exceeded the vibration level of the undamped ground return by up to five times.

(iv) When only one spacer/damper was installed near mid-span, the use of three vibration dampers at the span end was effective in reducing the bundle vibration to the level of that of the ground return conductor.

(v) The field test method was used successfully to measure both the conductor torsional stiffness and the conductor damping ratio.

INTRODUCTION

The problem of vibration in single and bundled conductors has a long history. Generally, the industry has accepted, more or less as a rule, that bundled conductor systems vibrate less than single conductors. This paper challenges that rule.

The tests reported here are aimed only at a comparison of vibration levels in single and bundled conductors (a bundle of three). For the first time, this paper develops a relationship between vibrations on a single conductor in the same span as a triple bundled conductor of the same diameter at the same tension, and at the same time. The only difference is between the single and bundled configurations.

Besides comparing the vibration of a single conductor with a bundle, a comparison is made for a span having only one spacer/damper at mid-span plus a single end-point damper at one end of the bundled span.

The narrow issues examined here are: (i) does the single conductor vibrate more than the bundled span, and (ii) does end-point damping plus one spacer/damper provide vibration protection?

The phase I portion of the New England Power Co. DC transmission line was constructed in 1985. It connects with a similar line of the Vermont Electric Co. and thence to the Hydro Quebec Interconnection with James Bay, Canada. The tests described here were performed on the phase I section, which comes into the state of New Hampshire near the Moore dam and reservoir, then runs more or less parallel to the Connecticut river to the Comerford station, where a converter changes the DC to AC power for local transmission. All of the tests were performed on span 18 - 19, chosen for its length of 1150 ft (348 m) and for its proximity to local AC power to drive the instruments.

The phase II portion of the line will also be DC at ± 450 kV, and will bring power from the Comerford station down an existing right-of-

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TABLE 1

Conductor characteristics

Item	American units	SI units
Conductor size	2 839 800 circular mils	
Diameter	1.986 in	50.4 mm
Area	2.327 in^2	1500 mm^2
Weight	3.018 lb ft^{-1}	5.52 kg m^{-1}
Diameter of Al aluminum wire	0.1986 in	5.04 mm
Number of Al wires	72	72
Diameter of steel wire	0.1324 in	3.36 mm
Number of steel wires	7	7
Rated tensile strength	64.8 kips	288 kN
Rated tensile strength of Al	48.1 kips	214 kN
Rated tensile strength of steel	16.7 kips	74 kN

way now carrying two 220 kV H-frame circuits built in 1927. The distance, about 120 miles (200 km), is through the state of New Hampshire, terminating at a converter station in Massachusetts. Construction of phase II began in 1988. The conductors are the same as those of phase I, and are described in Table 1.

Figure 1 shows the steel pole H-frame used in phase I, structure 18. The two bundled conductors are on either side of the structure. The single ground wire return conductor is seen in the middle of the arm, while the two overhead static wires are at the top of the angled cantilever arms. Foundations are caisson type, without bolted anchor plates.

The conductors consist of a bundle of three subconductors in an inverted delta having a top separation of 25 in. (0.63 m) and a vertical separation of 13 in. (0.32 m). The single ground return conductor is the same as the subconductors, having the same AGS suspension, and the same tension. The spacer design, seen in Fig. 2, is a three-arm aluminum design having a single pin pivot at the center with a rubber bushing. A close-up view of the inverted V-string is seen in Fig. 3, and that of the spacer/damper in Fig. 4.

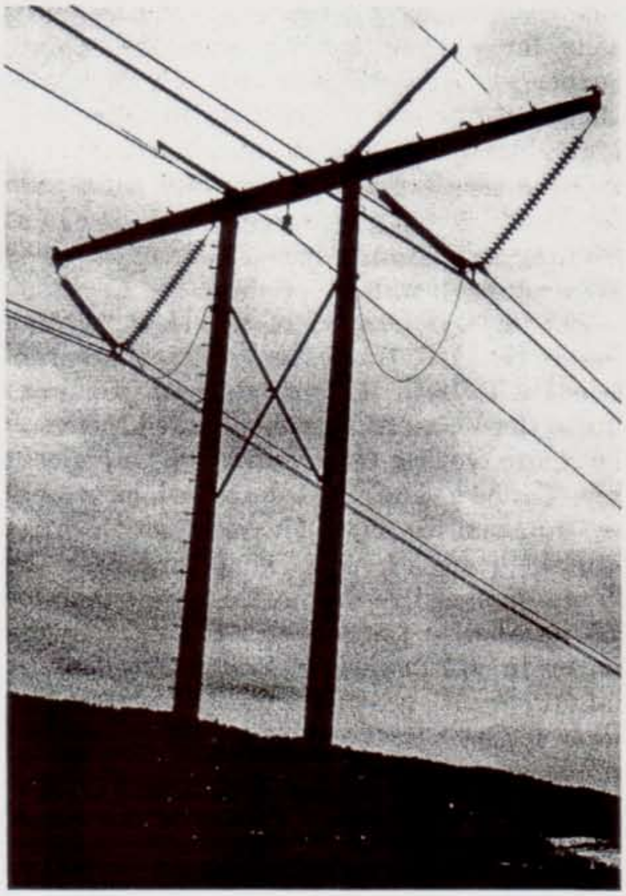

Fig. 1. Steel pole H-frame.

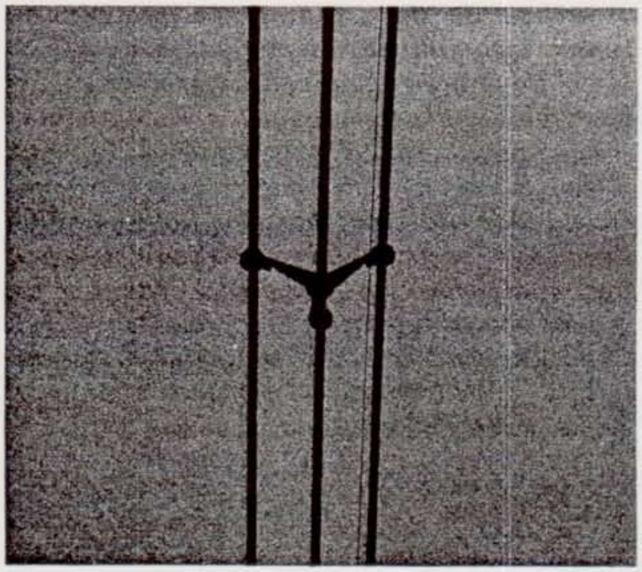

Fig. 2. Spacer/damper.

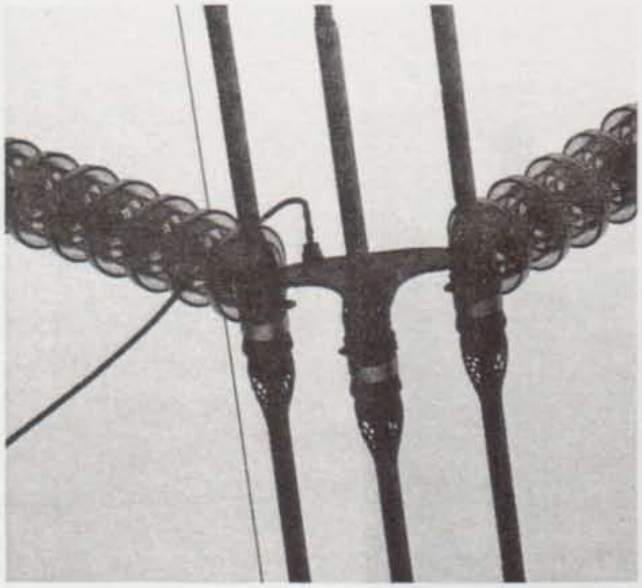

Fig. 3. Suspension assembly.

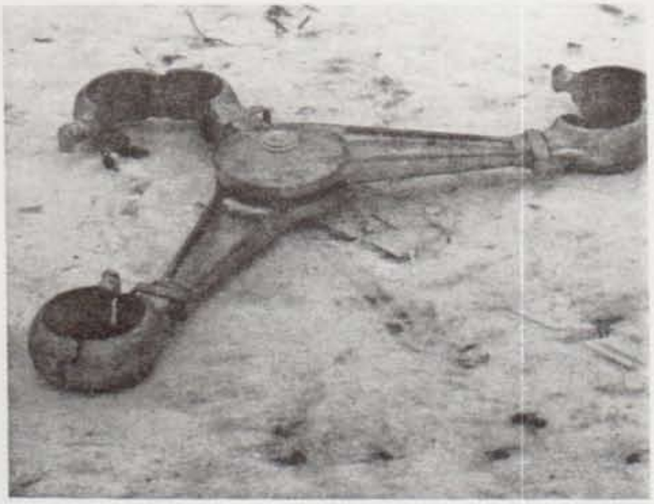

Fig. 4. Spacer/damper close-up.

There are five of the spacer/damper units on the span 18 - 19.

The overall view of the 1150 ft (348 m) span is seen in Fig. 5, while the closer view of structure 19 and the trolley used to remove the spacers is shown in Fig. 6.

The instrumentation consisted of the R/T system [1]. This is a system developed by this author and Teledyne Engineering Services, Inc., Waltham, MA. Figure 7 is a photograph of the system which was located in a nearby house about 400 ft (121 m) from structure 18. A typical time trace record is seen in Fig. 8. The top trace is the vibration of the single ground return conductor, while the bottom trace is the vibration in the bottom subconductor. The heart of the system is the fast Fourier transform analyzer (FFT), manufactured by Nicolet. This unit, together with a printer and two matched strain gauge type accelerometers brings on-line computer capability into the field vibration test arena. The accelerometers were manufactured by Statham Instruments. They were calibrated in the laboratory before the tests, in the field during the tests, and in the laboratory after the tests. Furthermore, the input cables to the FFT analyzer were interchanged several times during the tests.

Fig. 5. Test span.

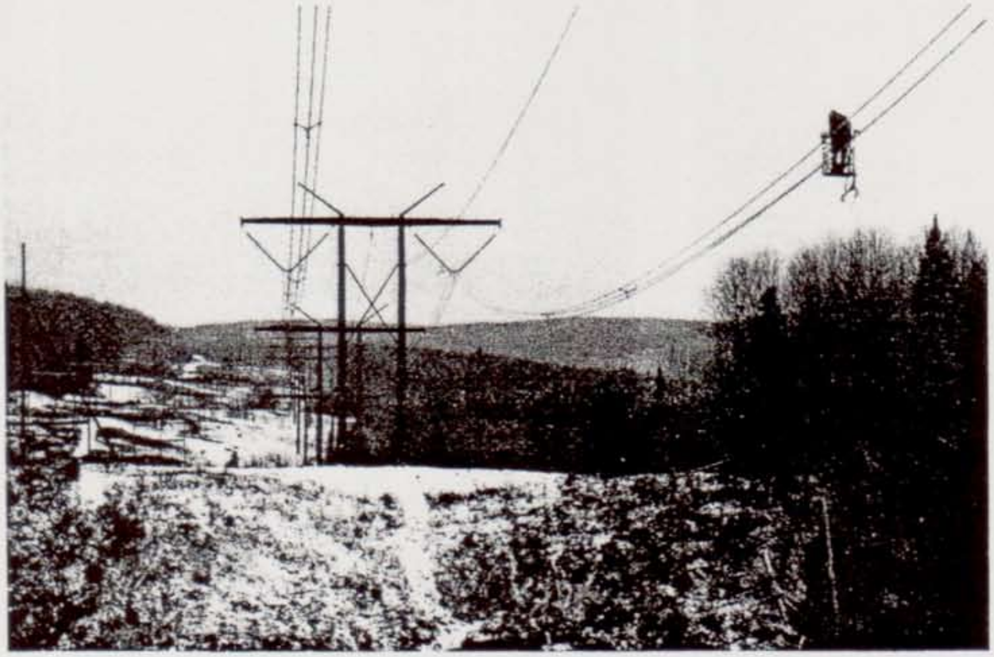

Fig. 6. Test span close-up.

The signals on the oscilloscope were transposed.

Finally, an end-point damper was installed in conjunction with one spacer/damper at mid-span. The end-point damper (AR type) is seen in Figs. 9 and 10. These dampers were located near the suspension point. The AR damper was calibrated as indicated in the Appendix.

DESCRIPTION OF THE DATA

The records show the type of print-out of the data collected from the tests during the test period of eight days. The records include the frequencies and dates shown, and some also include time response data. The frequency range recorded is zero to 20 Hz, corresponding to zero to approximately 15 m.p.h. ($6 \mathrm{~m~s^{-1}}$).

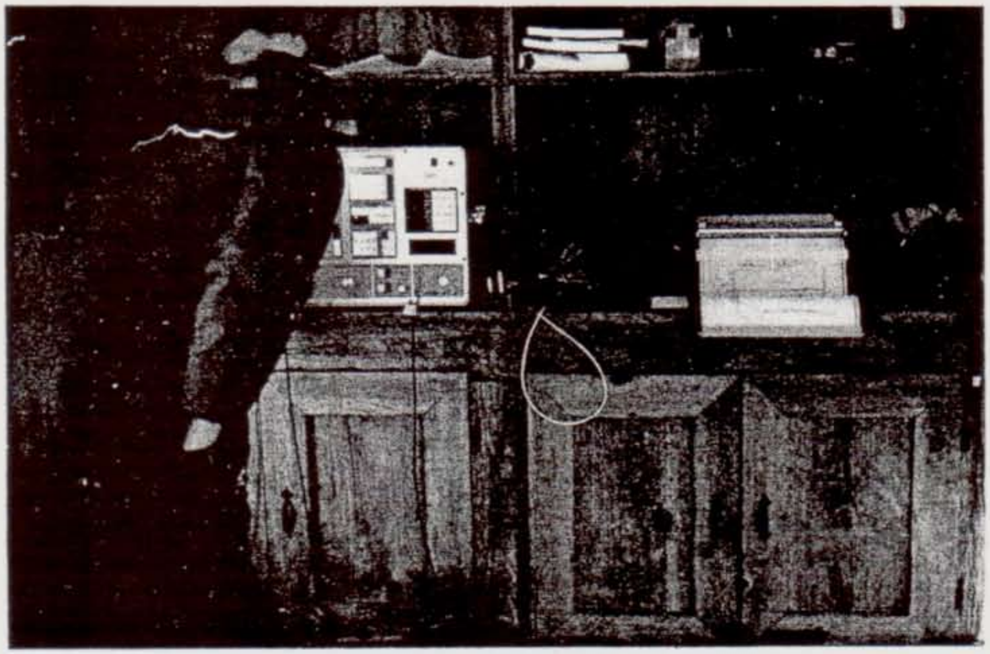

Fig. 7. Instrumentation.

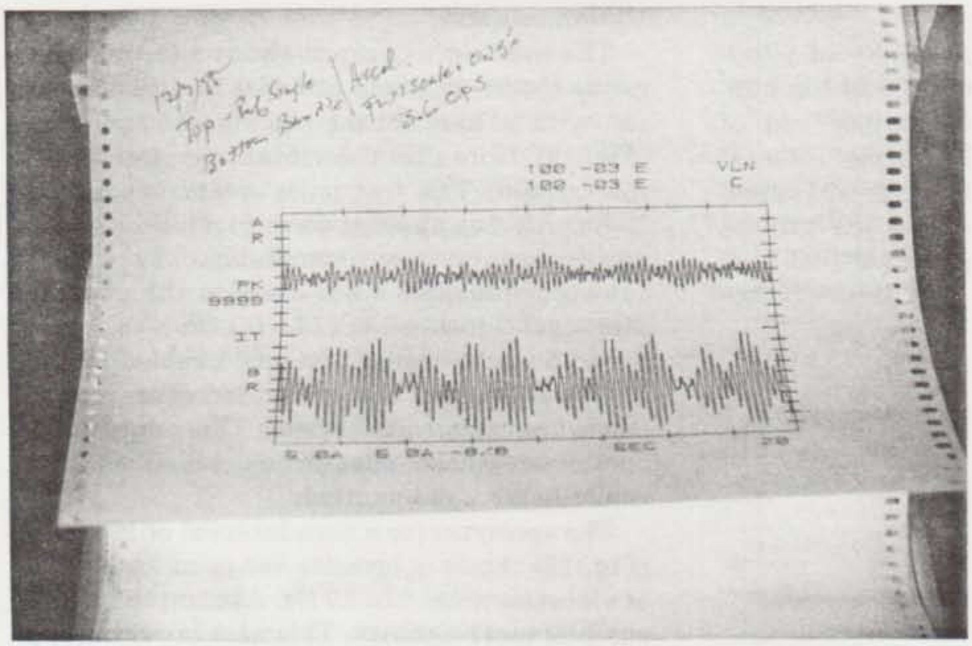

Fig. 8. Sample of test data.

In general, two forms of data were collected, time test data and frequency test data. The former show the vibration taking place in real time during a period of several seconds. The latter show the distribution of the frequency of the vibration, and the relative amplitude at each frequency. In the latter, the frequency scale is usually linear from zero to 20 Hz, but a log scale is used in a few cases. Two types of frequency spectrum may be identified. The first, and most usual, represents a long-time record of up to twenty hours, including overnight recording, and captures *all* vibration taking place in that time interval. The spectrum print-out shows the maximum RMS value of the vibration acceleration at each of the identified frequencies. This is one of the features of the Richardson/Teledyne system [1]. The second type of spectrum is an instantaneous breakdown of a particular time trace, showing only its components, which usually represents only several seconds of data.

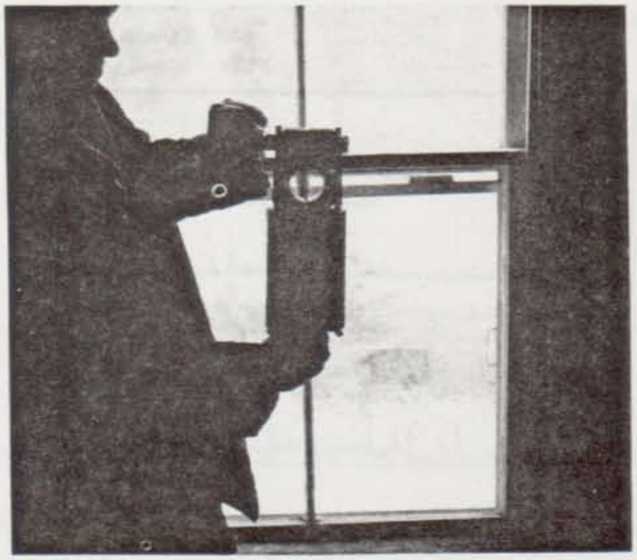

Fig. 9. Vibration damper.

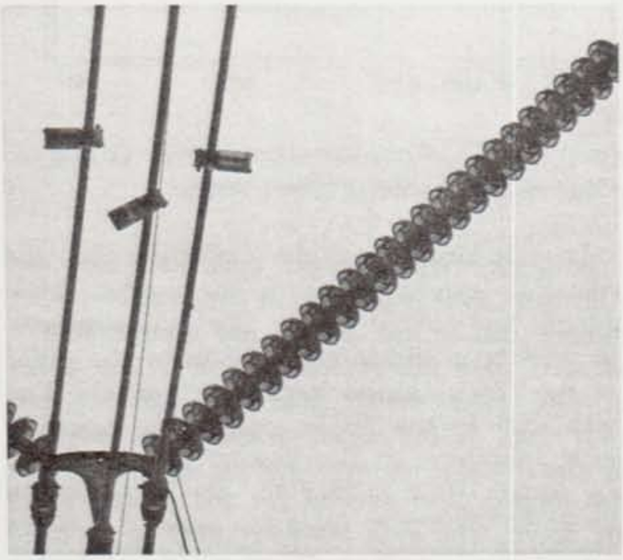

Fig. 10. Vibration dampers installed.

Conductor kick tests

These tests illustrate the activity of vibration on the single ground return and the bundle, following a kick to the armor rod of the AGS unit (Fig. 11). The time interval shown is about 20 s. The 3.79 s interval represents the time from the kick on the ground return to the time shown by the vertical line. It may be used to identify any desired time interval.

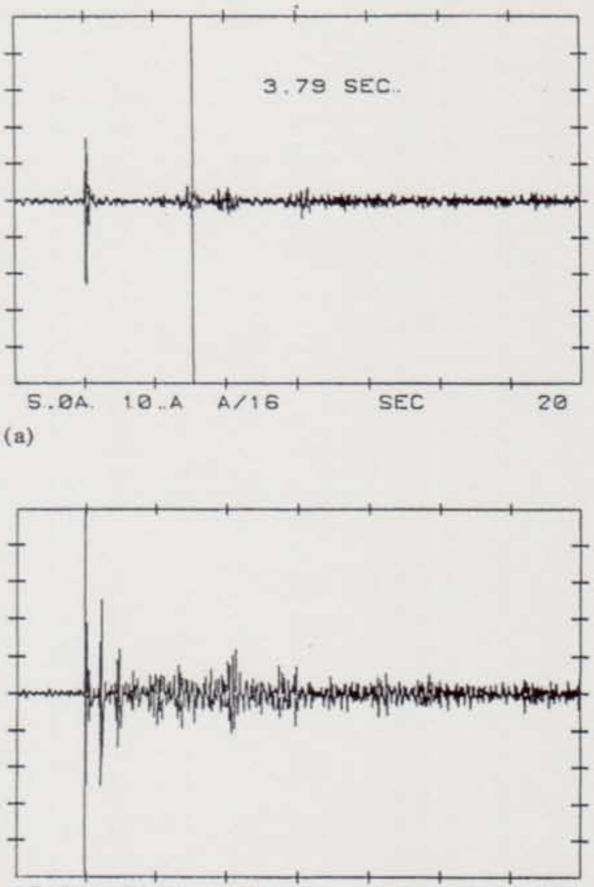

Fig. 11. Kick test response (Dec. 6, 1985): (a) kick on ground return; (b) kick on bottom bundle.

It is apparent from the kick tests that the vibration level is greater in the bundle—even though the initial pulses are comparable—as seen by a direct comparison of the pulse in the lower graph near the vertical line with that in the upper graph. The damping in the bundle is also lower, as seen from the longer time needed for the vibration to die down. The kick tests are easy to perform and give a quick indication of conductor damping.

Vibration tests

The next set of graphs shows the instantaneous spectrum taken at 4:00 p.m. in comparison with a longer time sample of two hours (Fig. 12). Note that the vibration is greater in the bundle. The frequency scale is zero to 20 Hz. All five spacers were in place, and all measurements were comparable. Two identical accelerometers were used on the conductors, each located 5 ft (1.5 m) from the armor rod and each feeding matched cables to each of two identical amplifier/recorders in the measurement/record system. The only difference was the conductor on which each accelerometer was mounted.

The spectrum for a time interval of 16 hours (Fig. 13) shows a broader range of frequency of vibration from 2 to 20 Hz. Again, the bundle exhibits more activity. This also is verified by the time trace in the lower graph. There appears to be significant vibration of the bundle at low frequency and/or low wind speed. Wind speed is linearly related to frequency. On the graph, a wind speed of 15 m.p.h. (6 m s^{-1}) occurs at a frequency of 20 Hz.

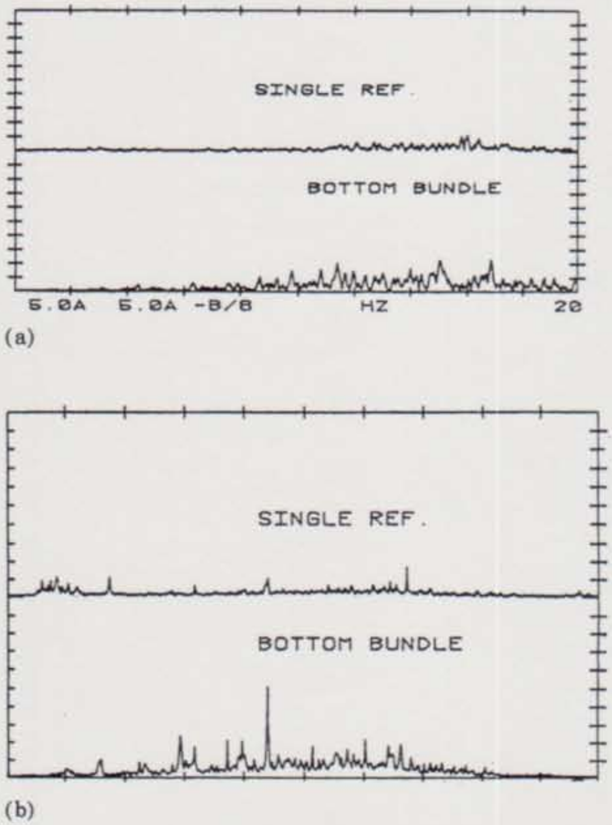

Fig. 12. Vibration spectra (Dec. 6, 1985): (a) instantaneous spectra, 4:00 p.m.; (b) maximum spectra, 2 h interval. (Scale: 0 - 30 m*g* RMS.)

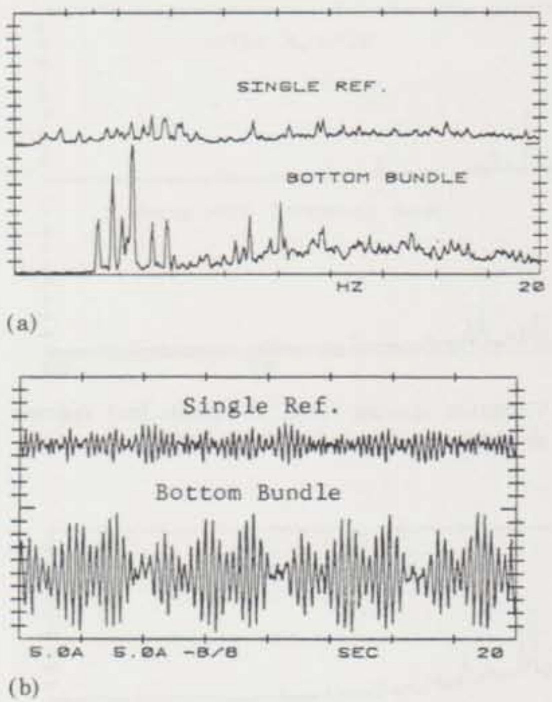

Fig. 13. Vibration spectra and time trace (Dec. 7, 1985): (a) acceleration frequency spectra, 16 h recording interval (scale: 0 - 50 m*g* RMS); (b) time trace (scale: 0 - 100 m*g*).

Additional records taken over a period of 18 hours (Fig. 14) again reveal the increased activity in the bundle compared with that in the single ground return. The instantaneous time trace record verifies this result.

At this point, the accelerometer was moved from the bottom of the bundle to the top subconductor, on the same side as the ground return. Again, all of the system quantities remained constant, except for the location of the two accelerometers. And again it was found that the bundle was more active than the single ground return conductor (Fig. 15). Then, two of the bundle spacer/dampers were removed, leaving three located centrally in the span. The result (Fig. 16), based on recordings of two and four hours, indicated *no* significant difference in the level of bundle vibration (Fig. 17).

Neither three nor five spacer/dampers were able to reduce the vibration of the three-conductor bundle below that existing in an *undamped* ground return conductor of the same size, tension, support hardware, and subject to the same wind environment at the same time. This was an unexpected result.

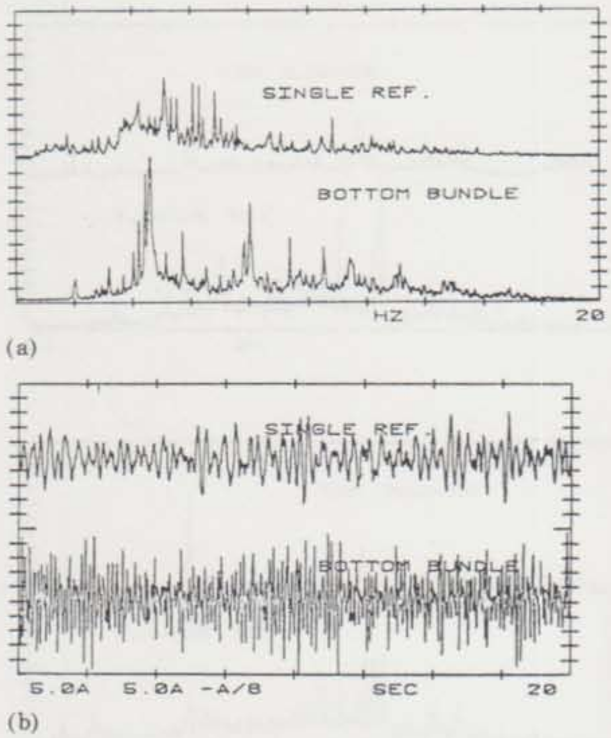

Fig. 14. Vibration spectra and time trace (Dec. 8, 1985): (a) acceleration frequency spectra, 18 h recording interval (scale: 0 - 30 m*g* RMS); (b) time trace (scale: 0 - 30 m*g*).

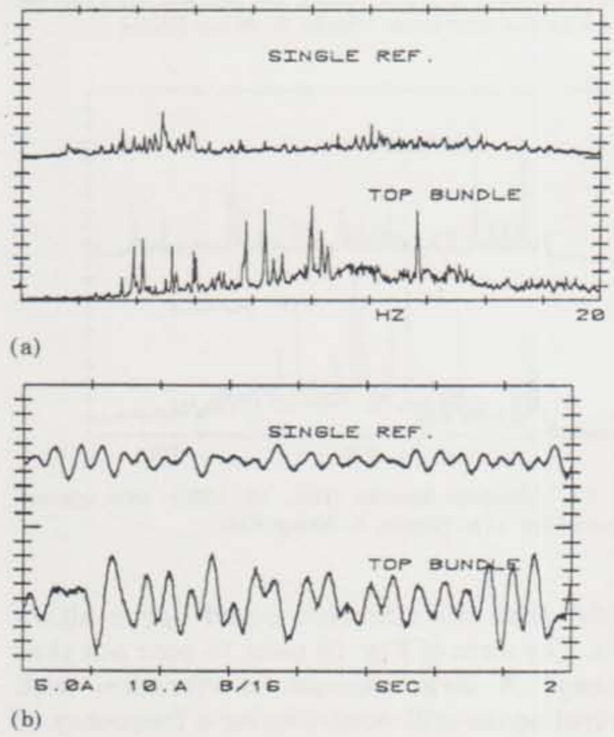

Fig. 15. Vibration frequency and time trace (Dec. 9, 1985): (a) acceleration frequency spectra, 18 h recording interval (scale: 0 - 30 m*g* RMS); (b) time trace (scale: 0 - 80 m*g*).

The next series of tests was performed using an AR damper and the removal of all except one spacer located near the mid-span. The AR damper acts like a filter for all vibration *above* its own natural frequency. The first series of tests used a natural frequency of 8 Hz. Theoretically, if the damper worked per-

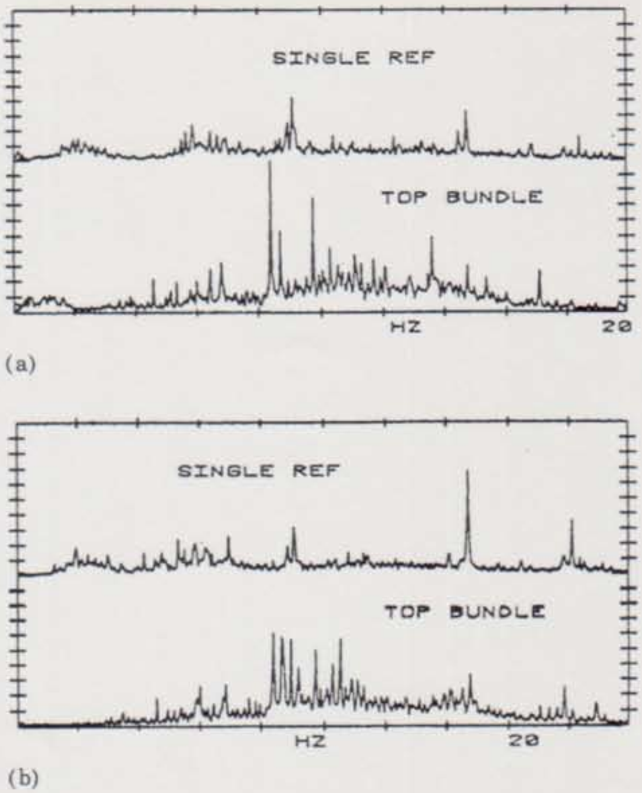

Fig. 16. Vibration spectra (Dec. 9, 1985): (a) two spacers removed for 2 h in the morning; (b) two spacers removed for 4 h in the afternoon. (Scale: 0 - 30 mg RMS.)

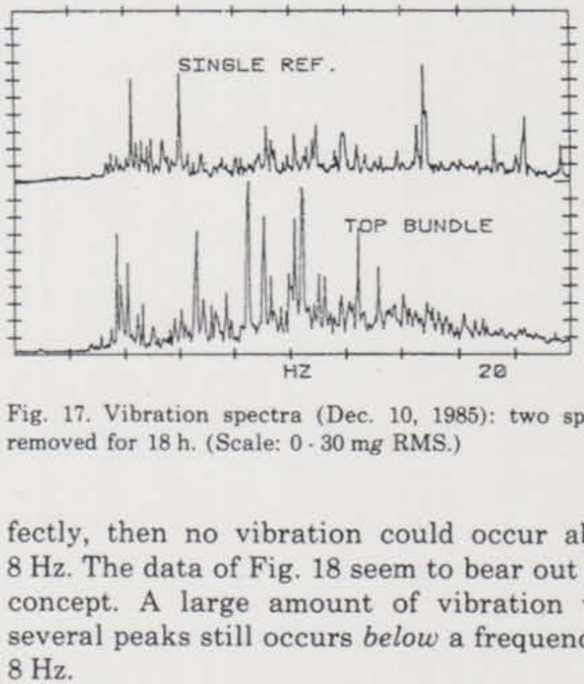

Fig. 17. Vibration spectra (Dec. 10, 1985): two spacers removed for 18 h. (Scale: 0 - 30 mg RMS.)

fectly, then no vibration could occur above 8 Hz. The data of Fig. 18 seem to bear out that concept. A large amount of vibration with several peaks still occurs *below* a frequency of 8 Hz.

Continuation of the test overnight reveals the same trend (Fig. 19). The AR damped high frequency vibration, but allowed low frequency vibration to pass. The time trace records show that levels of vibration at a frequency of 3 - 5 Hz are comparable between the bundle and the single reference (Fig. 20).

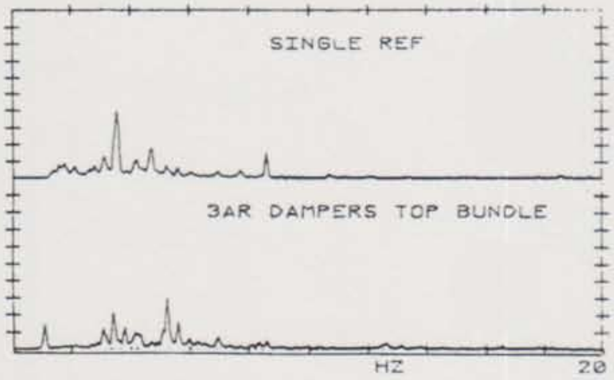

Fig. 18. Vibration spectra (Dec. 12, 1985): four spacers removed at 10:00 a.m. (Scale: 0 - 50 mg RMS.)

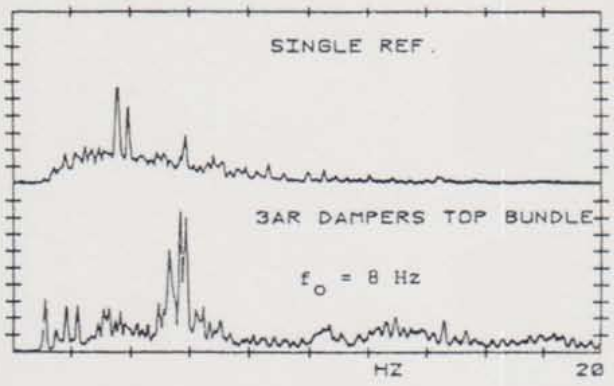

Fig. 19. Vibration spectra (Dec. 12, 1985): four spacers removed for 20 h. (Scale: 0 - 50 mg RMS.)

The next test involved a change in the natural frequency of the AR damper. The test revealed a natural frequency of 3 Hz and a damping log decrement of 12%. Use of that damper on the bundled conductor reduced the bundle vibration to a level comparable with that of the single conductor (Fig. 21). The frequency of the vibration was 9 - 10 Hz. The log spectra and the time trace agree as to the data.

It is evident that the use of one AR damper set at a natural frequency of 3 Hz or 8 Hz reduces the vibration level of the bundle to that of the ground conductor. The use of one damper per subconductor with one spacer/damper at mid-span reduces the vibration of the bundle by a factor of 3 - 5.

ANALYSIS

The test results have demonstrated two major conclusions: (1) the bundle always vibrates more than the undamped single ground re

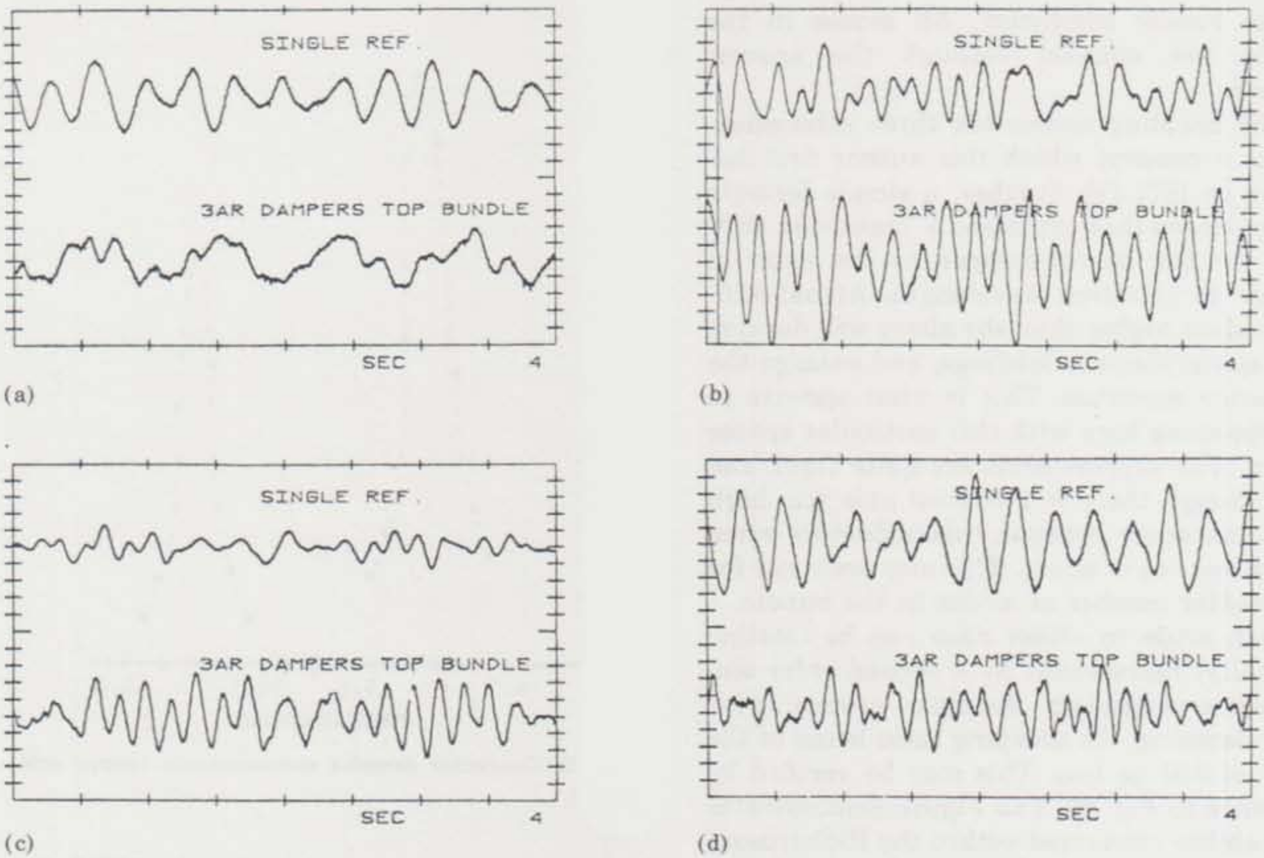

Fig. 20. Vibration time samples (Dec. 12, 1985): four spacers removed at (a) 10:25 a.m., (b) 11:01 a.m., (c) 11:06 a.m., and (d) 11:45 a.m. (Scale: 0 - 30 mg; damper natural frequency = 8 Hz.)

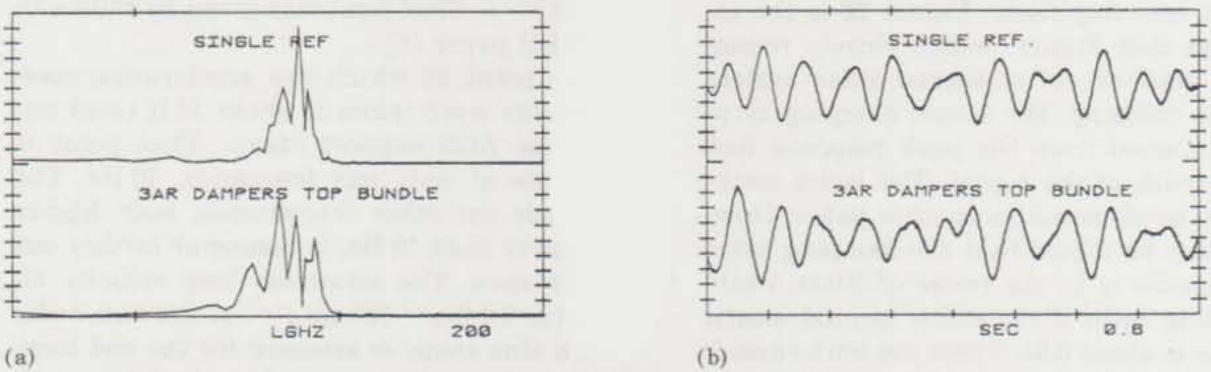

Fig. 21. Comparison of log vibration spectra and time trace (Dec. 12, 1985) after damper change to $f_0 = 3$ Hz with four spacers removed at 15:49: (a) scale: 0 - 12.5 mg; (b) 0 - 100 mg.

turn, and (2) the addition of end-point damping to each subconductor with only one spacer/damper at mid-span brings the vibration level down to that of the ground return.

It is worthwhile postulating what may be happening. First, there is clearly more activity in the bundle, both with respect to the vibration level and to the number of vibration lines in the spectra. These lines each represent a single mode that is excited at its resonant frequency. There simply are more of them in a triple bundle—three times as many as in the single. To put it another way, the modal density of the single is estimated at 5 modes per Hz, while the modal density in the bundle is estimated at 15 modes per Hz. Each Hz represents a wind speed range of 1 ft s^{-1} (0.3 m s^{-1}), so a change of wind speed from 6 to 7 ft s^{-1} (1.8 to 2.1 m s^{-1}) will cause 5 modes to be excited in the single conductor, but 15 modes in the bundle conductor. All modes in the bundle are coupled through the spacer/dampers.

This coupling among the three subconductors is a concept which this author first discussed in 1971 [2]. Further, a simple formula was proposed that expressed a 'transition stiffness' for the spacer/damper as the ratio of tension to vibration wavelength. Actual stiffness values higher than the above will develop high spacer/damper loadings, and enlarge the frequency spectrum. This is what appears to be happening here with this particular spacer design. The support arms are quite rigid, and even though there is a central axis pin, high loads can occur between subconductors when they move out of phase. This also accounts for the greater number of modes in the bundle.

Each mode in either case can be (mathematically) represented by a second-order single-degree-of-freedom dynamic system with small damping, the damping ratio being of the order of 0.01 or less. This may be verified by reference to Fig. 22. The Figure demonstrates a capability contained within the Richardson/Teledyne system, namely, that it can expand any portion of the line spectra and blow up the details, while spotting digital read-out of frequency and amplitude. Figure 22 is the result. From that Figure, which closely resembles the response of a second-order system with light damping, the actual damping ratio can be obtained from the peak response and the bandwidth of the signal. The latter methods are to be disclosed in another paper. However, it may be stated that the damping ratio for the bundle is in the range of 0.003, while the damping ratio of the single ground return conductor is about 0.01. These are both considered sufficiently high to avoid fatigue damage. The damping ratio is discussed in ref. 3, as for laboratory test spans.

The limit expressed by Diana *et al.* [3] may also be found in a paper by Richardson [4], except that in the latter the μg parameter is used, g being twice the damping ratio, and μ the relative density. The product μg has also been called the 'reduced damping'.

For this conductor, the parameter μ is equal to 2820. An acceptable product for safe vibration is $\mu g \geqslant 9$ [5]. Here we have, for the ground return conductor, $\mu g = 68$, and for the bundle, $\mu g = 19$. The latter is with the spacer/dampers, and the former is with no dampers.

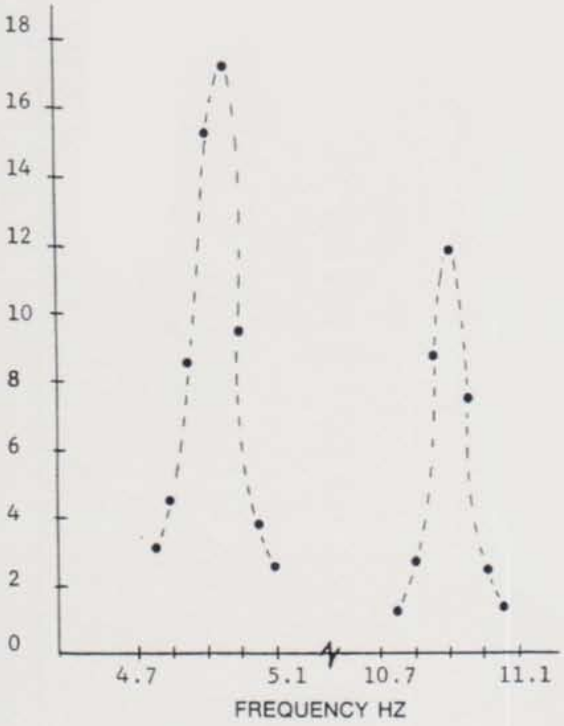

Fig. 22. Conductor damping measurements. (Scale: arbitrary.)

Another criterion, related to the IEEE 150 microstrain limit, is simply the statement that 'loop velocity should not exceed $0.6\,\mathrm{ft\,s^{-1}}$ ($20\,\mathrm{cm\,s^{-1}}$)'. That limit was given by Pullen in an IEEE paper [6].

The point at which the acceleration measurements were taken is about 10 ft (3 m) out from the AGS support clamp. That point is anti-node at only one frequency, 10 Hz. The anti-node for other frequencies, both higher and lower than 10 Hz, is nearer or farther out on the span. The maximum loop velocity allowed is $0.6\,\mathrm{ft\,s^{-1}}$ ($20\,\mathrm{cm\,s^{-1}}$) at the anti-node.

If a sine shape is assumed for the end loop, at each frequency a simple calculation will indicate the loop velocity from the measured acceleration. Such a procedure has been checked with known laboratory test data, and found to be accurate [3]. Here, the procedure is best employed in the case of the ground return. All such loop velocities calculated are less than $20\,\mathrm{cm\,s^{-1}}$.

CONCLUSIONS

(1) The vibration of a single conductor is less, by up to 4 - 5 times, than the vibration of

a triple bundle having five spacer/dampers of a particular type.

(2) The level of vibration of a bundle having only one spacer/damper at mid-span and one end-point damper per subconductor is the same as that of the single conductor.

ACKNOWLEDGEMENT

It is with sincere thanks that I acknowledge Mr. Frank S. Smith of the New England Power Service Company, who encouraged me to publish this paper.

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APPENDIX

AR damper calibrations

Before any tests were performed on the bundled span, certain tests were first performed on the damper itself. These first tests were to determine (1) the damper's natural frequency, and (2) its damping characteristics. The outcome of those tests may be seen in Figs. A-1 and A-2. Figure A-1 is the result of an initial twisting displacement of the damper about the conductor axis, and its release to oscillate on its own. The lineman was instructed how to sit on the bundle so as not to disturb the damper response. The signal, seen in Fig. A-1, is the acceleration of the top subconductor due to a damper also on the top subconductor. Both the log decrement and the damper natural frequency can be found from the simple response test. These are, respec-

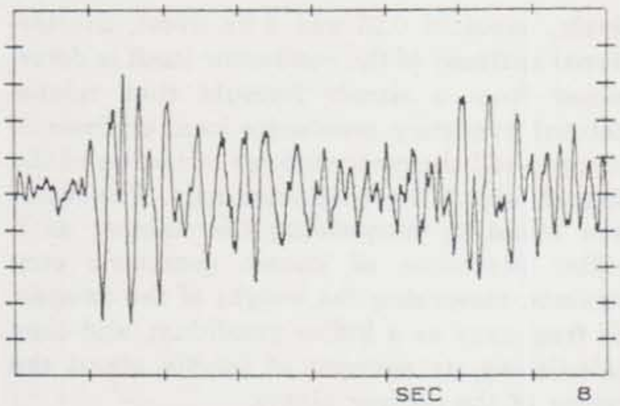

Fig. A-1. Damper response test (Dec. 11, 1985). (Scale: arbitrary.)

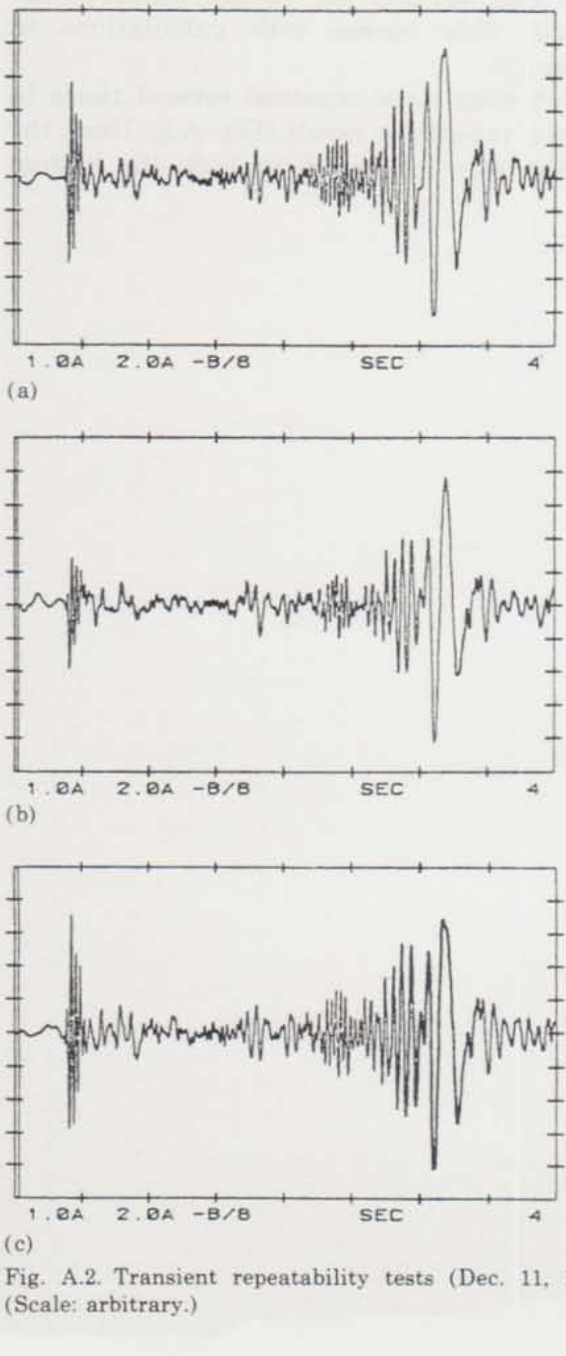

Fig. A.2. Transient repeatability tests (Dec. 11, 1985). (Scale: arbitrary.)

tively, equal to 0.23 and 3 Hz. Next, the torsional stiffness of the conductor itself is determined from a simple formula that relates natural frequency, conductor local stiffness in torsion, and the mass moment of inertia of the damper about the conductor axis. The latter was found by suspending the damper as a bifilar pendulum of known geometric constraints, measuring the weight of the damper, its frequency as a bifilar pendulum, and then calculating its moment of inertia about the center of the damper clamp.

The numerical value of the conductor local stiffness at 10 ft (3 m) from the suspension point was 464 lb ft per radian (625 N m per radian). This agrees with calculations to within 5%.

Kick tests were repeated several times to insure a repeatable result (Fig. A-2). Here, the lineman was instructed to kick the bottom subconductor while holding onto the upper subconductor not yet equipped with the damper. The initial pulse seen is the transfer from the bottom to the top (dampered) subconductor through the yoke assembly. The second pulse is the wave striking the accelerometer near the damper after having passed down the line to mid-span, through the spacer/damper and back. The round trip takes about 2.8 s. This agrees with earlier measurements made on the undamped ground return conductor to determine sag from round-trip travel time. Those measurements yielded a numerical value of 5.5 s. The actual sag was found to be 30 ft (9 m), by sighting a transit from a known point on structure 18 to a known point on structure 19, the line of sight being just tangential to the sag point at mid-span. Having made these preliminary measurements, the tests on the bundle then proceeded as described in the text.